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VENUS

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16. Abstract

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VENUS

Mikhail Ya. Marov

An extremely important stage has been broken through in the understanding of Venus due to the studies carried out in recent years by means of space probes and, in particular, to the measurements performed in situ in the atmosphere and on the surface of the planet. /927*

We know today that the surface of this planet is not, as was imagined 20 years ago, a hospitable environment where some form of life might exist, but quite contrarily, a burning inferno where crushing pressure is prevalent. But Venus is a unique world, ...**.

The revolution of Venus about the Sun takes 224.7 days and occurs on a practically circular orbit, with a radius of approximately $108.1 \cdot 10^6$ km, which is 0.723 times the mean distance between the Sun and the Earth. Every 584 days — its synodic period — Venus assumes practically the same position with regard to our planet and the Sun; in other words, it appears to us in the same fashion, in the same phase. Two of these positions are especially important: when Venus is situated between the Sun and the Earth, at /928

* Numbers in the margin indicate pagination in the original foreign text.

** Translator's note. Illegible.

inferior conjunction, it is at its minimal distance from us — about $40 \cdot 10^6$ km, but unfortunately it shows us its hemisphere submerged in the shade; and when it is situated on the other side of the Sun, at superior conjunction, the distance from the Earth is maximal, and it shows us its illuminated face. The apparent diameter of Venus varies greatly between these two extremes, between 64 seconds and 9.9 seconds of arc.

By its dimensions, mass, and density, Venus is very similar to the Earth; its radius (6050 ± 0.5 km) is 0.948 times the radius of our planet, the ratio of its mass to that of the Earth equals 0.81, its mean density 4.86 is only slightly lower than the terrestrial 5.52.

Besides, it is not the surface of Venus proper which we see, but rather a cloudy layer of uniform appearance which permanently surrounds the planet. The presence of this thick layer explains our ignorance of certain essential features of the Venusian world: first of all, the period of its own rotation, its dimensions, the properties of its surface, and its topographical relief. The ignorance is just beginning to be lifted, owing largely to the radar soundings which are being performed from different radio observatories. It is
now known that Venus turns very slowly, in the course of 243 days, /929
in the retrograde direction (an observer standing above the Venusian north pole would see the star rotate in a clockwise direction). This retrograde movement distinguishes Venus from all the other planets in the solar system, with the exception of Uranus, which is another special case. As a result of the planet's own rotation and of its revolution about the Sun, a Venusian "day" lasts 116.8 terrestrial days*, and any observer living through this day would certainly be surprised: the Sun rises in the west and sets in the east. "day" and "night" last for about two of our months*.. Besides, since the axis of rotation subtends an angle of less than 3° with the perpendicular to the orbital plane, there are no seasons on Venus.

*Translator's Note: As printed in foreign text.

Studies performed by means of radar soundings [1] have shown that the Venus globe is not a perfect sphere: in the equatorial plane, the section through the planet is an ellipse, the major axes of which differ by 1.1 ± 0.35 km, while the semimajor axis forms an angle of 55°, in clockwise direction, with the Earth at inferior conjunction. The center of gravity is displaced by 1.5 ± 0.25 km from the geometric center. The radar soundings have proven to be extremely useful for the investigation of the relief and of the physical properties of the Venusian surface. In particular, these soundings have made it possible to obtain maps which show how different regions of the planet reflect the radioelectric waves. Figure 1 depicts the reflection by the Venusian disk of centimeter waves, obtained by Rodgers et al. [2]; highly reflecting regions are clearly /930 distinguishable, which extend over hundreds and even thousands of kilometers. What is the nature of these regions? Two explanations can account for their high reflecting power: first of all, the altitude, which causes a reduced atmospheric absorption; then the variations in the properties of the soil, especially its texture, and its dielectric permittivity. The mean value of the latter is of the order of 4 to 4.5, according to radar soundings.

Studies performed at the radio-observatory of MIT in Haystack have revealed differences of 3 - 4 km of altitude in the equatorial region of Venus [3]. It is possible that even more elevated formations exist in certain regions. It can also be noted that the reflection of radioelectric waves on the planet takes place in a mirror-like fashion, with a polarization which is inferior to that caused by a reflection on the Moon. This attests to the fact that the Venusian soil is, on the average, less rugged than that of our natural satellite. This result is confirmed by the blunt aspect and the relative shallowness of the craters observed in a small equatorial region of Venus in recent radar probings (see illustration).

The first estimation of the mechanical properties of the Venusian surface was performed during the flight of the probe Venus-7 [4]. The modification of the signals received upon landing permitted

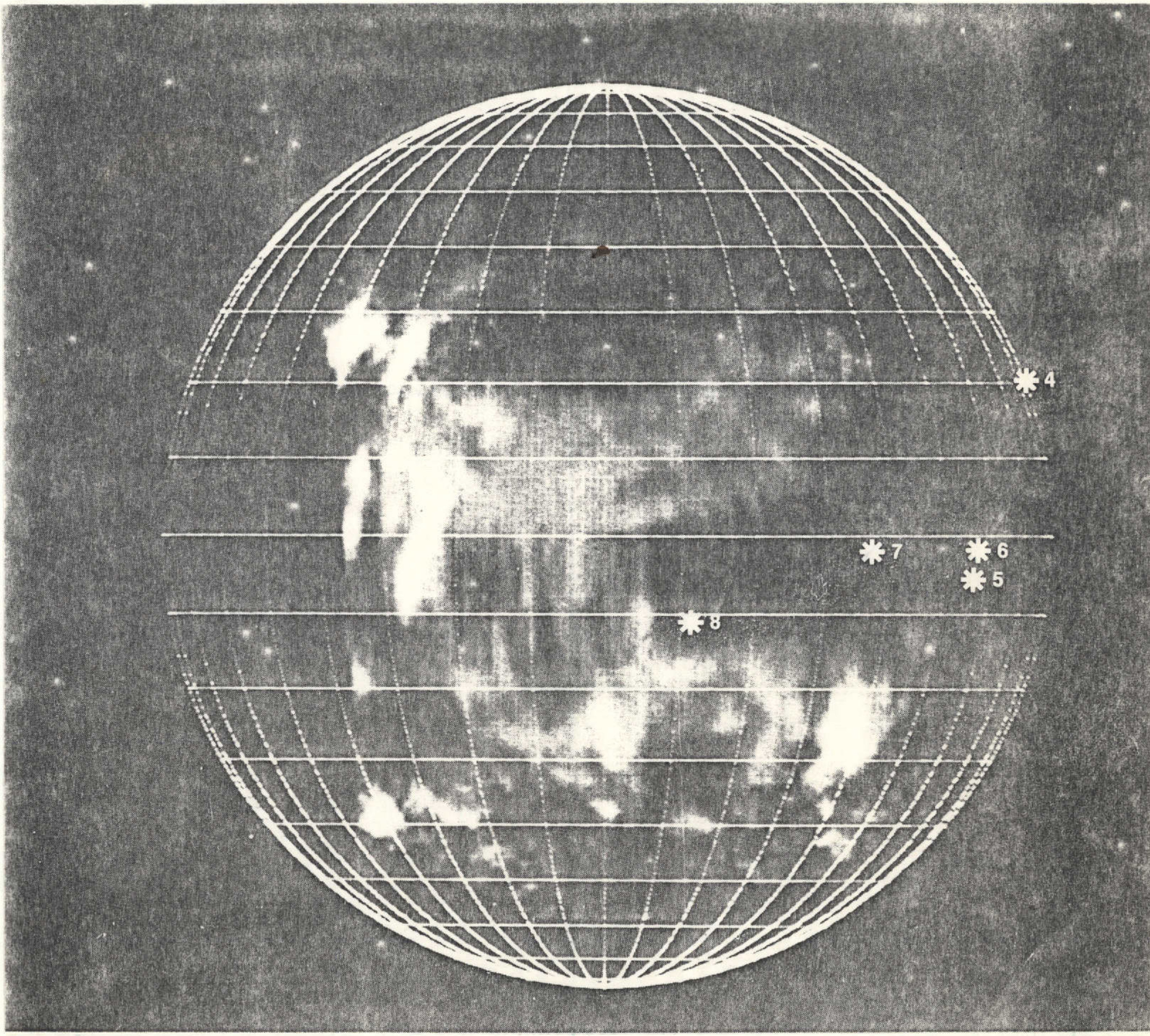

Figure 1. Reflectivity map of the Venusian disk in the range of centimeter waves determined at MIT in 1969. Highly reflecting regions are seen which correspond to surface inequalities or are due to physical properties of the soil. Elevations of 3 - 4 km were observed in the equatorial regions in the course of other experiments. The stars drawn on the disk indicate the landing site of probes

determining that the vertical speed of the instrument became equal to zero in less than 0.2 seconds. This corresponds to a shock against a solid surface, since the impact in a liquid or a thick layer of dust would have been much more gradual. Subsequently, simulations performed on the Earth allowed us to make estimation on the resistance encountered by Venus-7 during its landing: anywhere between 80 and 3 kg/cm^2, probably closer to the lower limit. The highest value corresponds on the Earth to volcanic lava, while the lowest — to wet clay.

The magnitude of the radioelectric waves reflected by the surface could be determined from the characteristic signals received by the radiometer of Venus-8 during the descent of this probe into the atmosphere, and this made it possible to estimate the dielectric permittivity of the soil. The obtained value is distinctly smaller, approximately by a factor of 1.5, than the values supplied by radar probings. This indicates that the region of landing of Venus-8 probably has a porous surface, made of an aggregate of small pieces of soil with a mean density on the order of 1.5 g/cm^3.

The mission of Venus-8 also permitted obtaining the first data on the nature of Venusian rocks [5]. The probe was equipped with a gamma-spectrometer so that measurements could be made of the intensity and spectral distribution of the gamma-irradiation of natural radioactive elements (uranium, thorium, potassium) in the composition of the soil where the station was placed. This made it possible to determine that this soil contained 4% potassium, 0.0002% uranium, and 0.00065% thorium. These proportions resemble those encountered in terrestrial granites.

At the surface of Venus: 750 K and 95 atmospheres

The presence of an atmosphere around Venus was detected for the first time by the Russian scientist Lomonosov in 1761, by observations made on the transit of the planet in front of the shining disk

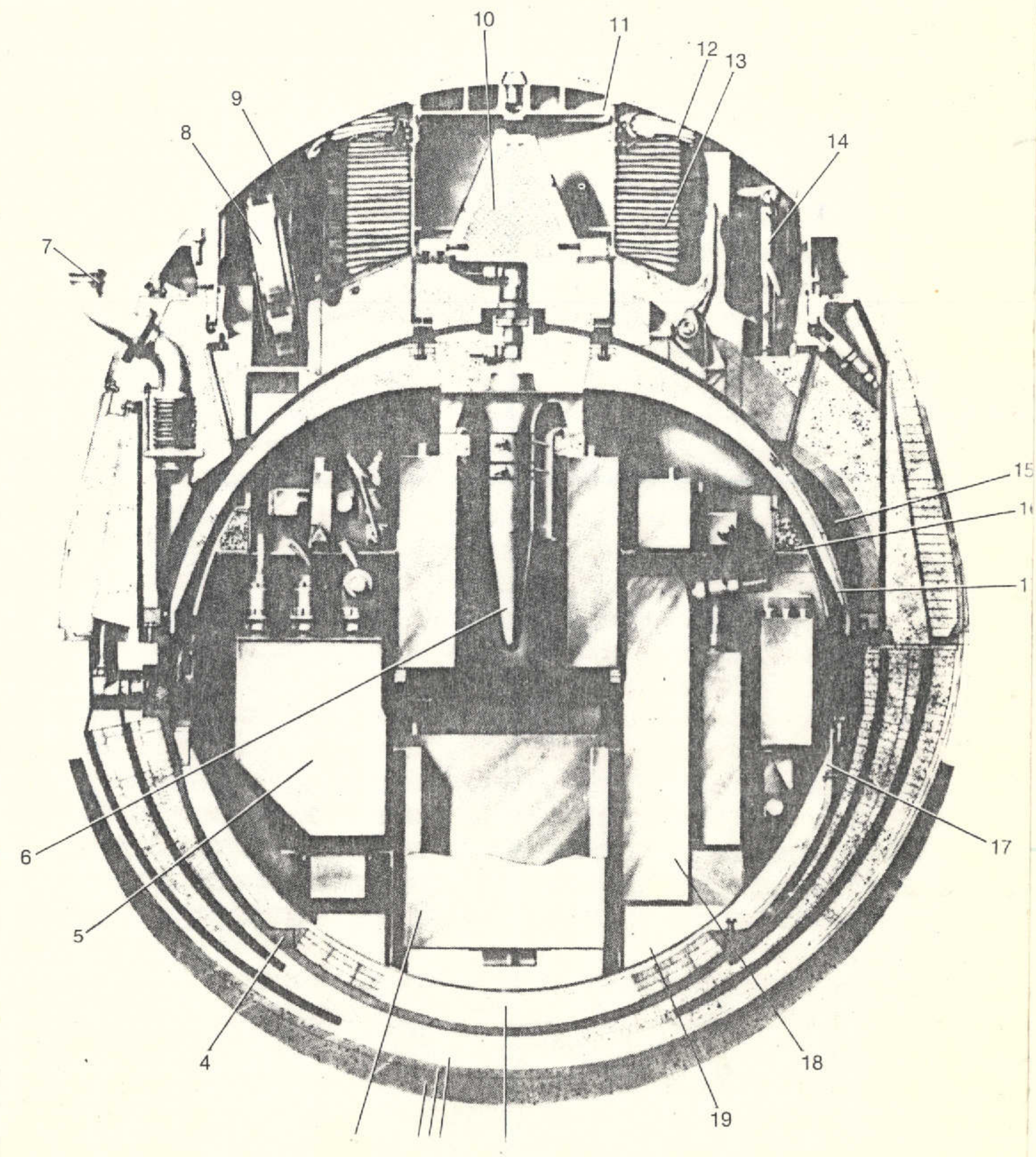

Figure 3. Diagram of the landing compartment of Venus-8:

1 — wobble damper; 2 — external thermal shield; 3 — transmitter; 4 — wall of the compartment proper; 5 — commutation group; 6 — fan; 7 — pipe of the thermal regulation system; 8 — antenna to be ejected after landing for functioning flat on the ground; 9 — parachute compartment; 10 — main antenna; 11 — roof of the parachute compartment; 12 — drogue parachute; 13 — main parachute; 14 — antenna of the radio-altimeter; 15 — heat exchanger; 16, 19 — heat storage accumulator; 17 — internal thermal isolation; *

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of the Sun. But two hundred years had to pass before the nature of this gas blanket could be determined. Why this long delay? Simply because of the cloud layer. The latter prevents any unequivocal estimation of the parameters of the lower atmosphere by means of optical instruments and, in particular, infrared spectrometric determination of its composition, pressure, and temperature profiles. Its influence on the results of spectrometric measurements conducted on the visible part of the atmosphere, which is situated above the clouds, is difficult to ascertain. High-precision spectrometric studies, with a resolution of 0.1 Å in the near infra-red have led to the detection of merely some gases — carbon dioxide, water vapor, carbon monoxide, fluorhydric and chlorhydric acids; the upper range of their concentrations was estimated, and the temperature and pressure at the summit of the clouds were determined (the height of that summit was not well defined at that time).

Again, data on what was happening under the cloud layer could only be supplied by radioelectric waves, and these were rather limited data, practically limited to the temperature. Measurements performed by different radiotelescopes at the end of the fifties revealed a strong emission in the range of centimeter radiation, which is characteristic for Venus. This emission corresponded to a temperature of 600 - 650 K for the planet surface, assuming that it had a thermic origin. This temperature, which is incomparably higher than those of Earth and of Mars, is not compatible with the theories which presented Venus as a star covered with oceans, with a rich flora, a kind of tropical paradise. In order to account for this occurrence without abandoning the above theories, non-thermic mechanisms were sought in order to explain the centimeter emissions of the planet, such as very dense ionosphere, electric dischages in the atmosphere, synchro-cyclotron radiations. But each one of these hypotheses stumbled on a series of contradictions. A little later, in situ studies of space waves proved the thermal origin of the Venusian radio-electric radiations: the measurements carried out by the author, Avduevsky, Rozhdestvensky and colleagues gave the following results by means of intercepters installed onboard Venus-7 and Venus-8: 747 ± 20 K and 743 ± 8 K, respectively, for the temperature of the surface of the star.

However, the Venus automatic stations could not measure at the same time the temperature and the pressure of the atmosphere near the Venusian surface. For the first time, they determined the composition of the part, previously mysterious, of the gas blanket which is situated below the clouds [6]. For this purpose, the Venus-4, 5, and 6 probes were equipped with simple instruments of gas analysis, using the methods of chemical absorption, change of electric resistance, and sublimation, in order to estimate the concentration of carbon dioxide, of nitrogen, and of water vapor. Venus-8 was able to measure the concentration of ammonia by a colorimetric method. The studies on the chemical composition performed by Vinogradov et al. [19, 20] were conducted at different levels of the atmosphere, corresponding to pressures of 0.6, 2, and 10 atmospheres, respectively. Their results were a great surprise: far from being the predominant element, as had been thought until then, nitrogen amounted to only 2% of the gas blanket; it may even be absent altogether. The main constituent is carbon dioxide, with a concentration of nearly 97% by volume. The oxygen concentration is below 0.1%; the content of water vapor varies between 0.1 and 1% near the cloud layer, while the concentration of ammonia is anywhere between 0.01 and 0.1%.

The spectrometric measurements performed from the Earth had /932
yielded much lower upper limits for the concentrations of certain gases than the values determined by the Venus stations: 0.001, 0.01, and 0.00001% for oxygen, water vapor, and ammonia, respectively. There is no discrepancy for oxygen, since the probe studies yielded only a higher limit, but the differences with regard to water vapor and ammonia are striking. They are due without any doubt to the fact that the concentrations were determined at different levels of the atmosphere: below the clouds — by the space probes, and above the clouds — by the spectroscopic techniques. Thus, the estimations made above the clouds can yield much lower values due to condensation.

Maximal values for the concentration of water vapor and of ammonia in the lower atmosphere were also supplied by investigation of the hyperfrequency spectrum of Venus. It has been found that the concentration of water vapor does not exceed 0.1%, which is compatible with the measurements of Venusian stations. With regard to ammonia, however, a large deviation is observed: the obtained values are 1/10 to 1/100 of the estimations made by Venus-8. The amounts of gases which are present in small amounts remain to be determined with accuracy by future measurements.

An extremely important result is, on the other hand, that the molecular mean of the Venusian atmosphere is 43.4 ± 0.6.

The changes in pressure and temperature in relation to altitude were directly determined by the stations Venus-4, 5, 6, 7, and 8 from the surface up to 55 km altitude and, indirectly, by the American probe Mariner-5, from 35 to 90 km altitude [7] (see Figure 4). Where-ever two types of measurements are available, the agreement is very good. It has also been observed that the temperature profile determined by the probes Venus-4, 5, 6, and 7 above the dark hemisphere was similar to that determined by Venus-8 for the illuminated side of the planet. The pressure on the soil at the site of landing of Venus-7 was 90 ± 15 kg/cm^2. In the region of landing of Venus-8, the pressure was 93 ± 1.5 kg/cm^2.

The data supplied by Mariner-5 indicate that a minimal temperature of about 160 K is reached by 90 km altitude. Above this level, no measurements were performed by space probes on temperature and pressure variations. However, the calculations performed by Dickinson [8] lead to the assumption about a second minimum, corresponding to 180 K at 120 km altitude. Studies performed in 1959, during an occultation of the star Regulus (alpha in the constellation Leo) by Venus, yielded information on the atmospheric density and the gradient in this region, which we shall call mesosphere by analogy with the Earth; it seems, thus, that the decrease in temperature with the increase in altitude is markedly slowed down in this region, but for the time being, different estimations of the temperature in the mesopause differ by 30 - 40°.

The temperature profile below 60 km altitude is in good agreement with a model of the atmosphere in convective equilibrium. The temperature gradient is sufficiently close to the value corresponding to an adiabatic variation, 8.6 K/km, for the deviation to be explainable by errors in the measurements. Studies of refractivity and hyperfrequency absorption performed during the occultation of Mariner-5 by Venus have shown, however, that some irregularities may exist - in particular, between 37 and 50 km altitude. /933

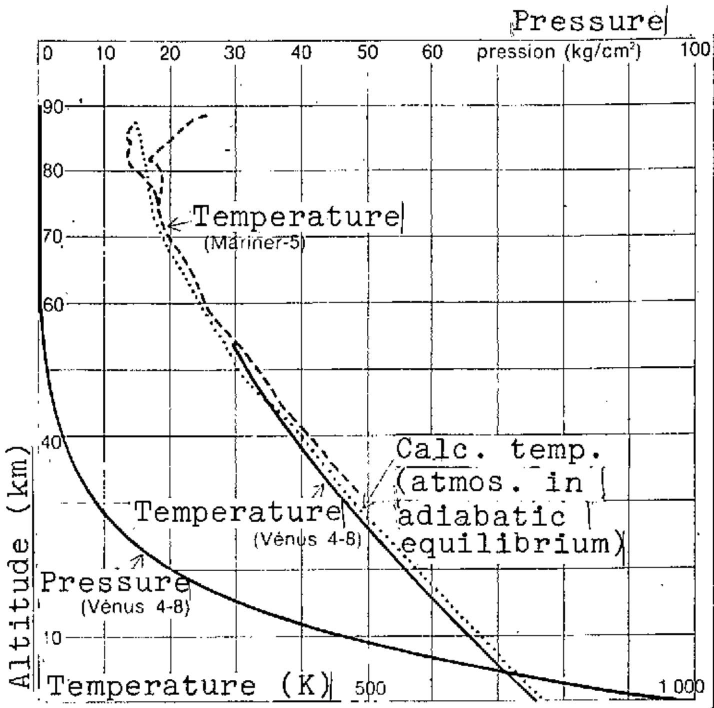

Figure 4. Pressure and temperature variation in the atmosphere of Venus in relation to altitude. The colored curve shows the mean profile of the temperature, determined directly by the Venus probes. The interrupted line describes the measurements performed during the occultation of Mariner-5. The dotted line was calculated on the assumption that the atmosphere was in adiabatic equilibrium. One can see that it practically coincides with the experimental curve traced by means of the data of measurements of Venus stations. The black curve gives the pressure values obtained directly by the two latter spacecraft (logarithmic scale). According to measurements of Venus-8, the temperature at the surface is 743 $\pm$ 8 K, while the pressure is 93 $\pm$ 1.5 kg/cm^2

There are due, without any doubt, to the presence of small amounts of certain constituents in the atmosphere. These constituents are not distributed in an even manner, but rather occupy special layers, according to their state diagram. What are these constituents? Undoubtedly, these are compounds which are volatile at a temperature of 750 K, the surface temperature, and are transferred into the atmosphere by the convective movements of the latter; they appear in the vapor or crystal state at different altitudes. The geochemical equilibrium between lithosphere and atmosphere was examined by Lewis, who investigated in particular the conditions under which mercury halide condensations could take place, between 250 K (corresponding to mercury chloride) and 450 K (mercury iodide). Besides, Rasool attempted to demonstrate experimentally the presence of such compounds on the basis of measurements of the attenuation of the Mariner-5 signals during the occultation of the latter.

Is the upper part of the clouds made of sulfuric acid droplets?

The subject condensation of certain compounds in the lower atmosphere of Venus leads us naturally to a basic problem, i.e., the nature of the Venusian cloud layer. This is a difficult problem, since in order to solve it, it is not sufficient to know the nature and the relative proportions of different atmospheric constituents, but the manner in which the equilibrium is established in the thermodynamic system in the several phases formed by these compounds must be understood.

Our main source of information on these clouds is, for the time being, the optical observations performed from the Earth, which are unfortunately limited to the upper part of the cloud layer. Some data obtained by Irvine with regard to the phase curve for monochromatic reflection and Nansen's calculations based on the results of polarimetric measurements are of special interest. The mean dimension of the particles could thus be estimated (about 1.1 μ), the albedo variations were studied in different spectral regions, the index of refraction of the cloud particles was estimated, etc.

Even taking into account the optical characteristics and the temperature and pressure profiles mentioned above, the available data are insufficient in order to determine the nature and the composition of the Venusian clouds. In addition, due to the fact that different elements or compounds may pass from the lithosphere to /934 the atmosphere, the possibility cannot be excluded that a complex structure exists with several layers in succession having different compositions.

The simplest hypothesis is that the clouds were formed of ice crystals. The data of the Venus probes with regard to the concentration of water vapor in the planet's troposphere show also that such clouds may exist, of course with some salts in aqueous solution, as is the case with terrestrial clouds.

If the concentration of water vapor is equal to 1%, the ice clouds should extend, starting with 59 km altitude, over a zone which is 10 - 15 km thick. If, on the other hand, the concentration is only 0.1%, condensation should start only at 68 km, and end by 110 km altitude (at a temperature of 160 K at this level), forming a diffuse layer of fog (see Figure 5).

However, numerous arguments contradict the theory of the ice clouds; the absence of characteristic absorption peaks of ice in the infra-red spectrum of the planet, between 1.5 and 2 μ; the high index of refraction (1.45 ± 0.02, while the index of refraction of ice is 1.31); the low transparence at wavelengths above 0.6 μ; the concentration of water vapor below the clouds which is very low, judging by spectroscopic methods.

The polarimetric and spectroscopic data lead to elimination of several other hypotheses with regard to the constituents of the upper part of the clouds - silica, hydrocarbons, iron chlorides, sodium, and ammonium chlorides. These data are in better agreement with another suggestion of Lewis [9], according to which the clouds are rich in an aqueous solution of hydrochloric acid. According to the spectroscopic data of Connes, the concentration of hydrogen chloride above the cloud layer is relatively small, about 10^{-7}. The equilibrium of phases is assured by assuming that the solution which composes the clouds has a hydrochloric acid concentration of about 25%. Good agreement is obtained, in particular, for the index of refraction.

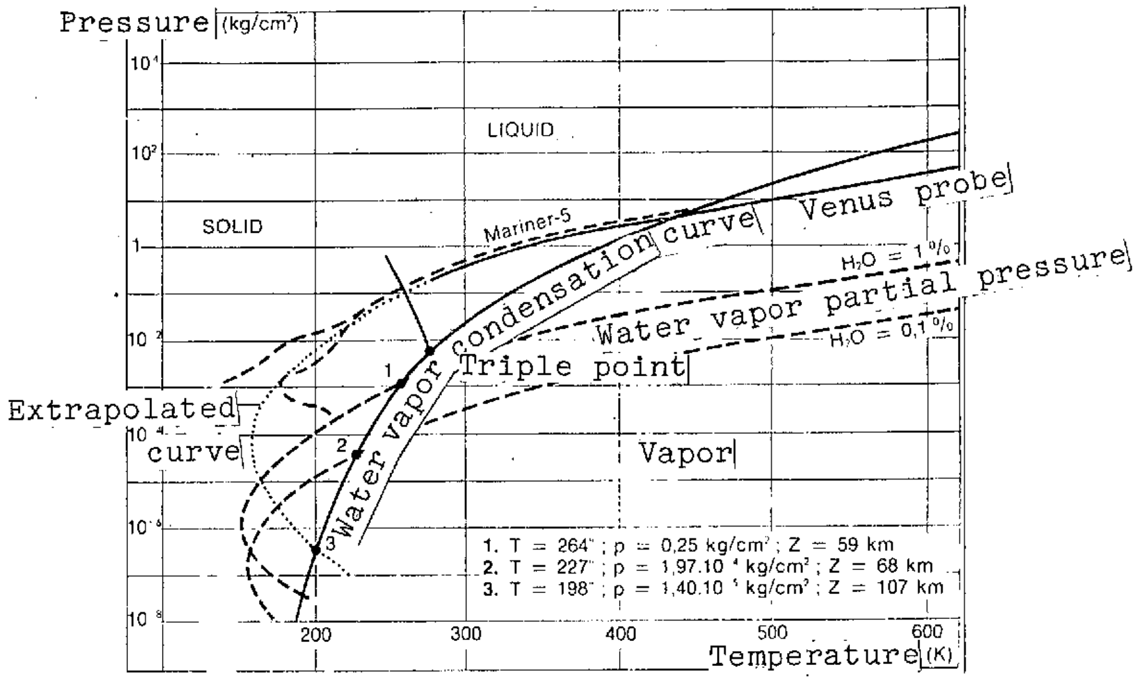

Figure 5. This is a diagram of the water states under conditions of variable temperature and pressure, in which the curves corresponding to the measurements of the Venus and Mariner-5 probes have been drawn; but since these curves do not extend to sufficiently low temperatures, they have been completed with a calculated curve for a model of atmosphere with a minimal temperature of 160 K. Under these conditions, the dotted curves give the partial pressure of water vapor for the concentrations 1 and 0.1%, i.e., for the upper and lower limits of the determinations performed by the Venus stations. The intersections of the curves with the line which marks the transition gas-solid correspond to the formation of clouds (points 1 and 2), at 59 km and 68 km altitude, respectively

Another recent hypothesis seems even more plausible; it suggests that the clouds are formed of sulfuric acid droplets in aqueous solution at a concentration of about 70 - 80%. In addition to the good agreement in the index of refraction, this hypothesis has the virtue of accounting for the difference between the concentration of water vapor above and below the cloud layer, the former measured spectroscopically, and the latter measured directly. Moreover, several recent experimental results [10] seem to confirm it: A. Y.

Young and L. G. Young from the Jet Propulsion Laboratory identified an absorption peak of sulfuric acid in the spectrum of Venus at 11.2 μ. G. T. Stiel from the University of Arizona showed that the spectrum of a 88% solution of sulfuric acid was similar to that of Venus between 1 and 4 μ; J. B. Pollack from the Ames Research Center of NASA determined with great accuracy the spectrum of the planet between 1.2 and 4.5 μ, from an airplane which flew at an altitude of 15,000 m. Subsequently, he compared this spectrum with those calculated numerically for several substances and obtained good agreement only for a solution of sulfuric acid.

Another argument in favor of this hypothesis is that it facilicates the explanation of why spectroscopic measurements had not detected sulfuric compounds in the atmosphere of Venus: the concentration of these compounds above the clouds, which are made of sulfuric acid in solution, is indeed very low.

Nevertheless, the final answer with regard to the nature of Venusian clouds can only come from studies performed by means of space probes.

The brightness at the surface of Venus, like under a stormy sky

Does the Sun's light reach the surface of Venus? This is an important question, not only in itself, but also for determining the mechanism of the high temperature which prevails on the planet. An answer to this question came from the experiment performed by the author, Avdouevsky and their colleagues by means of the station Venus-8 [11]. This probe was equipped with a cadmium sulfide photoresistance photometer, which is sensitive between 0.4 and 0.8 μ, and can withstand a temperature of 500° C at a pressure of 100 atmospheres; this instrument recorded both the radiation coming directly from the Sun and the light diffused by the atmosphere. This is a positive answer, although the light which reaches the soil is largely diminished to 1/100 of the light at the top of the clouds. /935

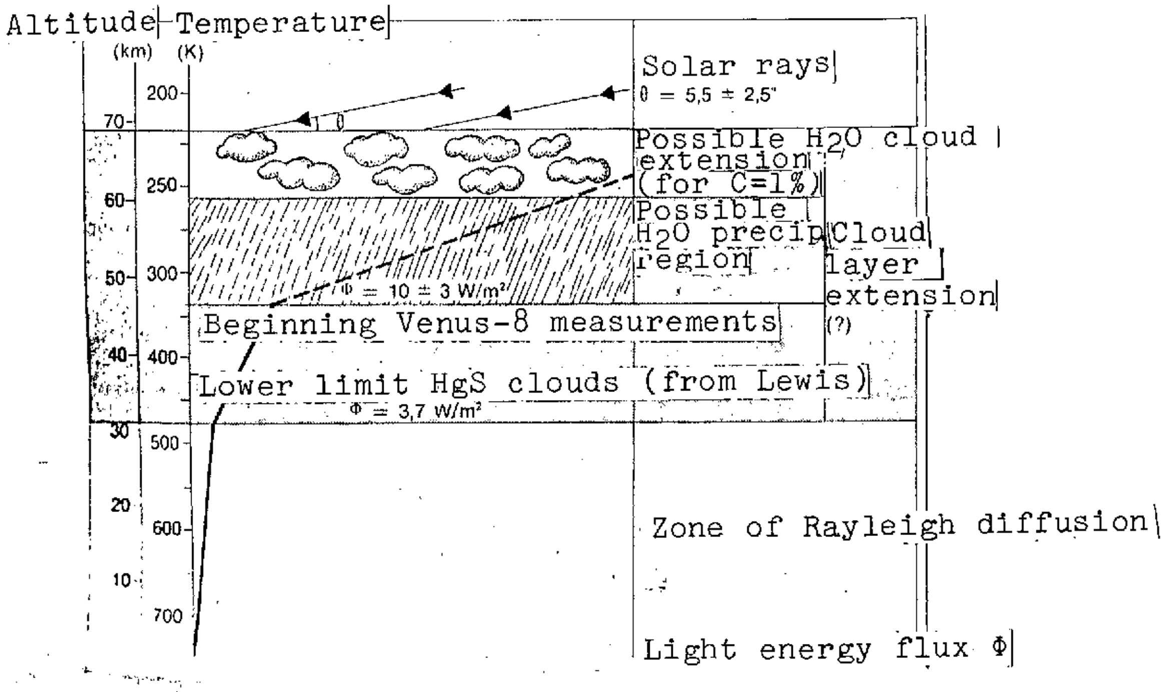

Figure 6. This diagram shows the variation of the light flux with altitude in the Venusian atmosphere, according to measurements of Venus-8, performed at a time when the Sun was 5.5° $\pm$ 2.5° from the landing site above the horizon. The continuous line corresponds to the measurements of Venus-8; the dotted line is an extrapolation between the light flux at the summit of the clouds, calculated according to the solar constant (with integral spheric albedo A = 0.77, according to Irvine), and the beginning of the probe investigations. Note the marked change in the slope of the variation curve at 32 $\pm$ 3 km. Below this level, the attenuation is readily explainable by Rayleigh diffusion; above it, the existence of certain clouds has to be assumed — for example, mercury halide clouds, as suggested by Lewis. A region of water precipitations, of "rain", could also exist and could contribute to the rapid decrease of the light flux

The measurements performed by Venus-8 were done at a time when the Sun was only 5.5° above the horizon from the landing site between the surface and 50 km altitude. These measurements showed that the light flux decreased in an irregular manner in relation to the altitude (Figure 6). Between the top of the clouds at about 70 km above the soil and at the beginning of the recording, at an altitude of 50 km, the light flux had decreased by a factor of 7. Subsequently, between 50 and 32 km altitude, it decreased regularly at a ratio of 3. From 32 km to the surface level, it changed again by a factor of 4, but with a lesser gradient. The change in slope at 32 km altitude observed in the curve describing the variation of the light flux is undoubtedly due to a modification of the mechanism of attenuation: below this level, it is readily explainable by a Rayleigh diffusion in the atmosphere of carbon dioxide, while above, a diffusion of aerosols has to be considered or else a true absorption. What is the explanation for this difference? It could be interpreted as an indication that the cloud layer extends up to 32 km altitude. But we indicated that ice clouds could not form at an altitude lower than 59 km. What is it then? Two possibilities can be envisaged: first, that it is not the clouds which descend down to 32 km, but rather a region of "rain"; ...* ice, but other substances such as, for example, the mercury halide compounds mentioned above, would condense at 35 km altitude.

And what is the brightness at the surface of Venus? It was about 300 lux at the site of landing of Venus-8, while the Sun was very low on the horizon. It would be on the order of 3,000 lux with the Sun at the zenith. Despite a large attenuation by the atmosphere, the illumination on Venus is thus comparable to that on the Earth under a stormy sky. It is, nevertheless, very hard to estimate the visibility. If the latter is sufficient, the strong refraction of the very dense atmosphere could lead to a surprising effect: an observer might get the impression that he finds himself on the bottom of a giant cell.

Greenhouse effect and convection equilibrium

In 1960, Carl Sagan [12] suggested that the elevated temperature on the surface of Venus is explainable by a "greenhouse effect". The measurements performed by Venus-8 show that he was right. Indeed, calculations show that the mixture of carbon dioxide with a small amount of water vapor behaves like a screen which prevents

*Translator's note. Illegible in the original foreign text.

the energy of the solar radiation, absorbed by the surface and by the atmosphere, to return to space. This leads to an increase in temperature and in pressure, which enhances even more the greenhouse effect, and this goes on until an equilibrium is established. An equilibrium ...* also geochemical. The cloud layer, which reflects without any doubt a part of the energy flux which leaves the lower atmosphere, certainly plays a role in the creation and maintenance of the Venusian greenhouse effect.

Calculations performed recently by the author and by Shari have shown that a radiation equilibrium is established only above 40 - 50 km altitude. Below this level, another mechanism must be responsible for the transfer of heat. Since the distribution of the temperatures is practically adiabatic, as we indicated above, this mechanism is undoubtedly a convection. Avduevsky and his colleagues showed that convection movements must take place at speeds of 0.05 to 0.2 m/sec, which is in good agreement with the estimation of the speed of vertical currents; this estimate was done on the basis of an analysis of the dynamics of descent of the Venus probes, accounting for the aerodynamic characteristics of the latter.

The Venusian atmosphere has a large enthalpy and, consequently, a considerable thermal inertia. This leads to very small temperature differences between day and night, less than 1 K at the level of the surface. This hypothesis is supported by the following two results: first, the measurements performed by the Venus stations, which we discussed above; second, determination of the temperature of brightness of the planet, according to the data of Sinclair, Gale, and their colleagues, at the wavelengths 3 and 11 cm, which correspond to the atmosphere and the surface, respectively; these determinations did not reveal any noticeable temperature variations ...* at 18 ± 9 K) or in longitude (smaller than 12 ± 6 K). The infrared /936
brightness temperature, the mean value of which on the Venusian disk

*Translator's note. Illegible in the original foreign text.

is 220 ± 10 K, and corresponds to an altitude close to 70 km, shows no noticeable diurnal variations, according to the data of Murray et al.

The stratosphere turns 60 times as fast as the planet

The thermal conditions prevailing on Venus are closely related to the dynamics of its gas blanket, in particular, the atmospheric circulation at the scale of the planet. An alternative to the theory of the greenhouse effect, based on a model of Venusian atmospheric currents, which resemble the oceanic circulation on the Earth, was suggested by Goody and Robinson [13], in order to account for the high temperature of the star. This hypothesis is practically discounted to date. But, even if the atmospheric circulation is not responsible for the heating of the planet, it certainly plays an important role in the thermal exchanges of the Venusian world, in particular, in order to bring heat to the polar regions.

Extremely interesting results on the horizontal movements of the atmosphere and on the structure of local turbulence were obtained by Kerzhanovich, the author, and others, by analyzing the descent trajectories of the Venus probes (Figure 7). In fact, each instrument brought information only on the winds at its site of entry. But in view of the enormous time of thermal relaxation of the atmosphere (about 10^{10} sec near the surface), the mean of the values supplied by the different probes can be considered to a certain extent representative of the global atmospheric circulation on the planet.

Above 15 km altitude, the Venusian winds have a zonal component which has the same direction as the planet's own rotation. The highest speed of the wind was measured by Venus-8 at about 50 km altitude and was higher than 100 m/sec. This speed decreased rapidly with altitude, and falls under 1 m/sec below 10 km. It is noted that between 18 and 30 km, the wind speed gradient is practically zero, while it reaches 5 m/sec · km on both sides of this strip.

The low wind speed at the level of the surface leads to the thought that the lower atmosphere probably does not contain much dust, which seems to be confirmed by the measurements of light flux performed by Venus-8.

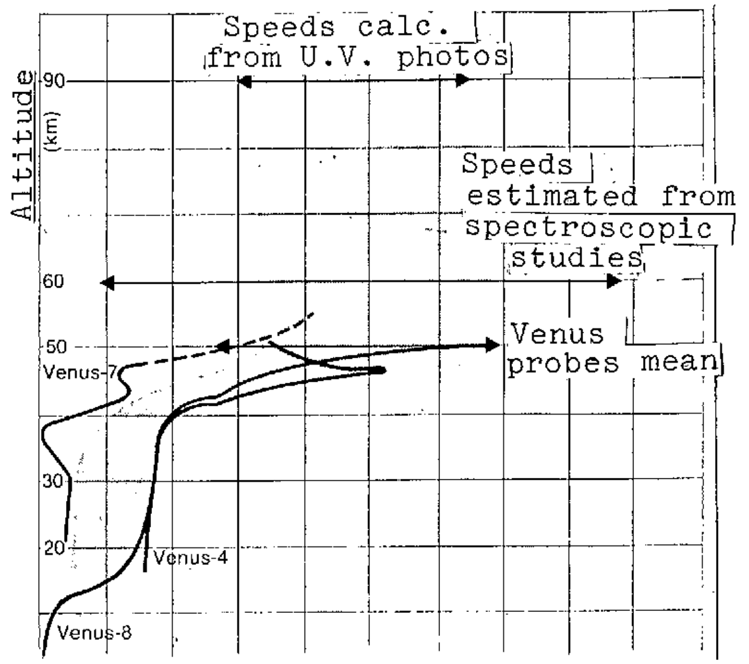

Figure 7. Speed of horizontal movements of the Venus atmosphere in relation to altitude, determined by analysis of the descent trajectories of Venus probes. The continuous curves give the experimental results for the different stations and their means. Allowing for the uncertainties of determination, the speed of Venusian winds should fall inside the hatched zone. Note that it is very low at the level of the soil (less than 1 m/sec) and that it remains so up to 10 or 12 km altitude, but increases rapidly subsequently, up to 50 or 100 m/sec. These winds move in a retrograde direction. Their speeds at high altitude are close to those of the atmospheric movements detected on the ultraviolet photographs

The rapid atmospheric movement at high altitude is undoubtedly related to a phenomenon which was brought to the fore by observations performed on Venus in the ultraviolet range [14]: the retrograde circulation of the Venusian stratosphere, which takes 4 - 5 days, is 60 times more rapid than the rotation of the star itself. This circulation, which corresponds exactly to a speed of about 100 m/sec, can be detected by following the displacement of certain irregularities which appear in the ultraviolet, at about 25 km above the summit of the visible clouds (Figure 8).

The terrestrial atmosphere also has a "super rotation", but this is found only at an altitude higher than 150 km, and it has a speed which is only 40% higher than the speed of rotation of the planet.

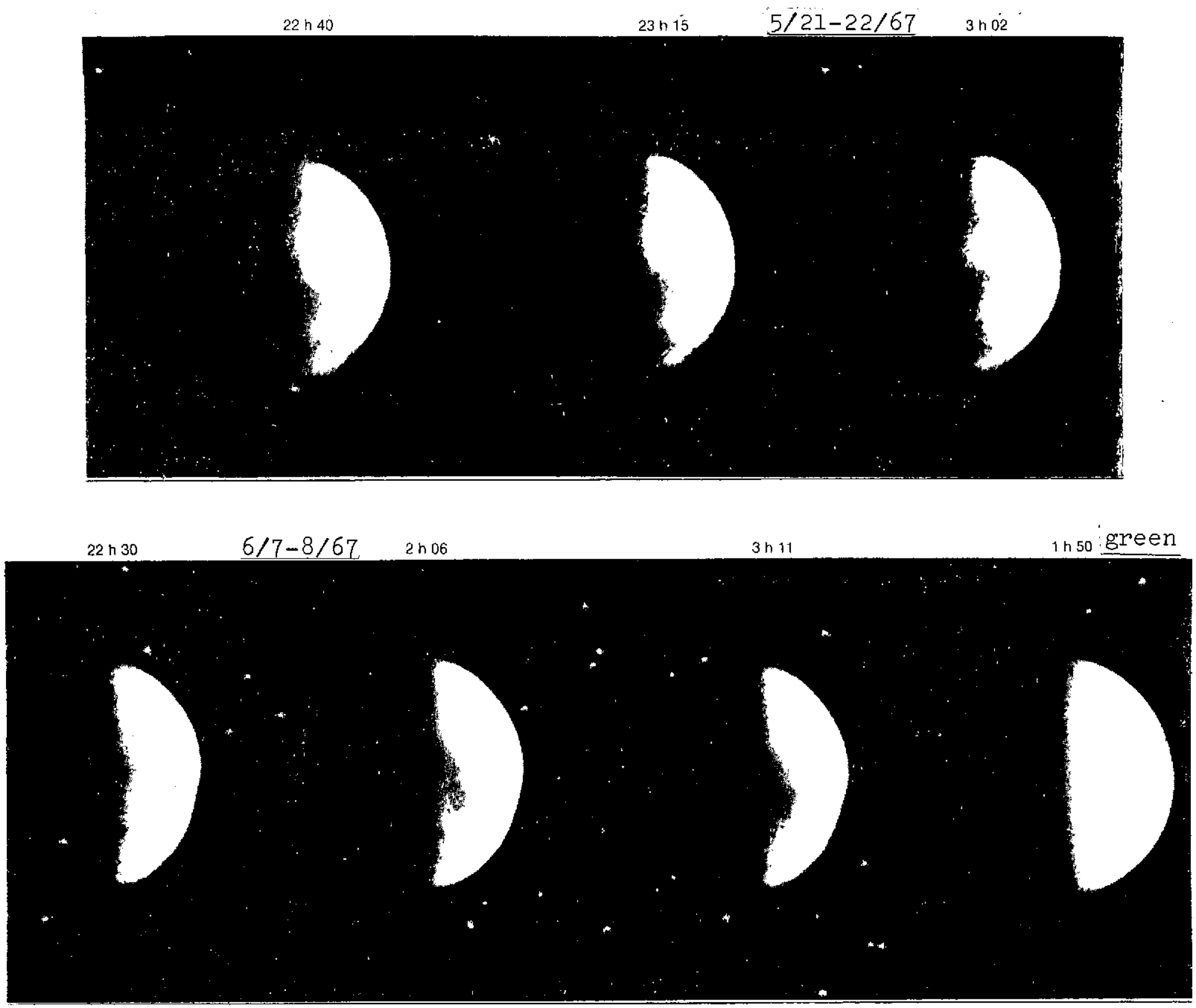

Figure 8. (Caption on following page)

Figure 8. (continued). These ultraviolet photographs taken by B. Smith show distinctly the irregularities which change place in every photograph. These formations complete a revolution of Venus in 4.4 + 0.02 days, which corresponds to a mean speed of displacement higher than 100 m/sec (the photographs were kindly supplied by B. Smith)

Dynamic processes and turbulent diffusion could explain the predominance of carbon dioxide

An entirely separate problem is the structure of the atmosphere of Venus at high altitude, in the thermosphere and the exosphere. The main data available on this subject were obtained by the probes Venus-4 and Mariner-5, during a period of medium solar activity. Under these conditions, the photometer installed by Barth onboard Mariner-5 led to the determination of the temperature of the exosphere starting with the Lyman-alpha emission of hydrogen [15], i.e., approximately 650 K. This estimation is in good agreement with theoretical calculations, which, by the way, permit us to forsee large temperature variations between 400 and 900 K, between day and night, on one hand, and in the course of the 11-year solar cycle, on the other. If the upper atmosphere of Venus were in photochemical equilibrium, atomic oxygen would be the predominant element at 200 - 300 km altitude, as a result of the dissociation of carbon dioxide, which is the main component in the lower atmosphere, under the effect of the ultraviolet solar radiation. However, spectrophotometric measurements performed by space probes showed that atomic oxygen had, in fact, a low concentration in the upper atmosphere. According to estimates of Donahue and Strickland [16], the concentration of atomic oxygen in the thermosphere does not exceed a few percent.

This surprising finding is confirmed by the profile of electron distribution in the ionosphere of Venus, determined by the Stanford group from the data of Mariner-5 [17]. In Figure 9, this profile is compared with theoretical calculations performed for various temperatures and ions. It can be seen clearly that the best agreement is obtained for the distribution of CO_2^+ ions. Theoretical calculations performed by McElroy lead to the same conclusion. The highest

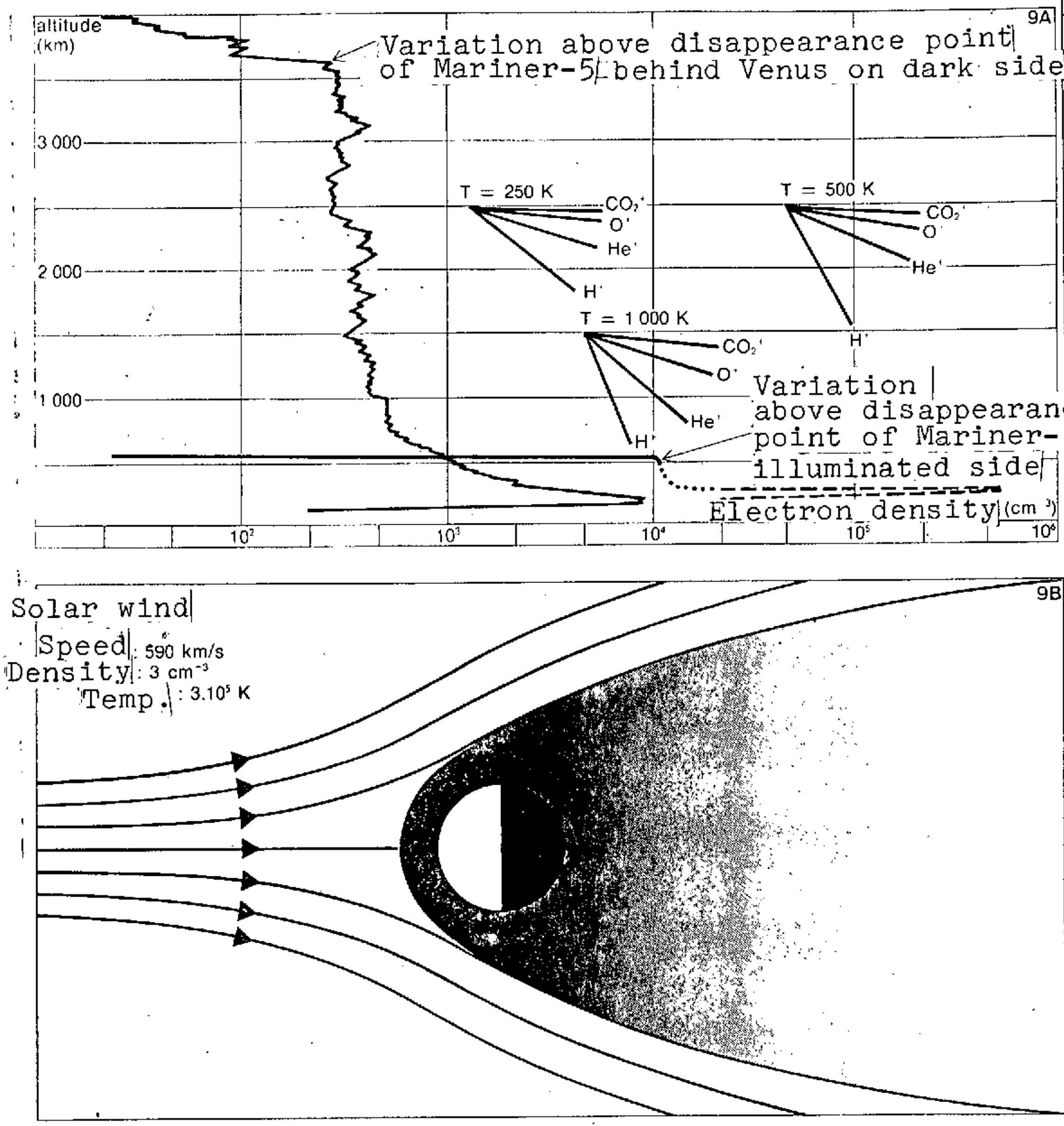

Figure 9. Variation of the electron density with altitude in the Venusian ionosphere, determined during the occultation of Mariner-5 by the planet (Figure 9A). The density above the dark area was measured in the moment of disappearance of the probe; the density of the illuminated side was determined upon its re-appearance. The rate of variation of the density with altitude, also called the "gradient" of this density, which is represented geometrically by the slope of the curve, supplies data on the composition of the upper atmosphere. The straight lines which form the bundles illustrated in the figure are the calculated slopes for several temperatures of the exosphere, and for different ions. One can see that up to an altitude of 300 km, the atmosphere is undoubtedly mainly composed of carbon dioxide, (which gives CO_2^+ ions after

(Caption continued on following page)

Figure 9 (continued). releasing one electron). Subsequently, after a narrow strip of oxygen (which yields O^+), hydrogen becomes the prevailing element. One notes above the illuminated hemisphere that the electron density falls sharply at a level higher than about 600 km, indicating the presence of a "ionopause" which results from the interaction between the ionosphere and the solar wind. The shape of this ionopause and the deformation in the trajectories of the solar wind particles are presented schematically in Figure 9B

electron concentration is found on the diurnal side at 142 km altitude, and amounts to $5.5 \cdot 10^5$ electrons/cm^3. This is one half of both the altitude and the density in the terrestrial ionosphere (F2 layer). The electron concentration is much lower above the dark hemisphere, about 1,000 electrons/cm^3.

This predominance of carbon dioxide in the thermosphere is not characteristic for Venus alone; it is also encountered on Mars. For the latter planet, highly interesting results were obtained by Barth by ultraviolet spectrometers onboard Mariner probes; in addition to the luminescence of atomic oxygen, these instruments have indeed detected a strong emission, quite unexpectedly, which originated in molecules of carbon monoxide and CO_2^+ ions; this emission leads to an important energy expenditure by the thermosphere. This expenditure, corresponding to the transition between levels of vibration energy, explains without any doubt the relatively low temperature of the Martian thermosphere, as well as of the Venusian thermosphere. As a matter of fact, the latter planet is undoubtedly the site of similar phenomena.

Both in the case of Mars and of Venus, the following explanation of the predominance of carbon dioxide in the thermosphere is generally accepted. This explanation, suggested by Shimizi and Dickinson, involves dynamic processes: first, the rapid circulation of molecules and ions between the illuminated and dark sides; second, the turbulent diffusion which plays a double role — first, it facilitates the transfer of atomic oxygen from the regions of dissociation to lower altitude zones which are favorable for the recombination of carbon dioxide; on the other hand, it assures the feeding or carbon dioxide from the region of dissociation. The coefficients of turbulent diffusion in the thermosphere are five times as high as on the Earth, but there are grounds to assume that such values can be reached in the upper atmosphere of Venus and of Mars. Above 250 km altitude, the recombination takes place at noticeably lower yields. This means probably that there is a relatively thin layer of atomic oxygen at about 300 km altitude ...* element, helium, becomes certainly very important. The profile of the electron concentration depicted in Figure 9 is readily explainable by the photo dissociation of the helium atoms above 250 km at an amount of $3 \cdot 10^7$ atoms/$cm^2 \cdot$ sec, accompanied by a horizontal transfer of ions formed on the dark side. Assuming that helium is produced at the same rate as on the Earth ($3 \cdot 10^6$ atoms/$cm^2 \cdot$ sec) as a result of the radioactive disintegration of uranium and ...* required for establishing, if 10% of the helium ions appearing on the illuminated side were carried into the interplanetary space as a result of interactions between the planet and the solar wind. /937

At an altitude higher than 1000 km, the predominant element becomes hydrogen, as indicated in Figure 9. This crown of hydrogen surrounding Venus was discovered by Barth and Kurt, and it resembles the geocrown, but for an extension ....* temperature of the Venusian exosphere. /939

On the side illuminated by the Sun, a steep decrease in electron concentration takes place at about 600 km altitude. This points to the existence of a "ionopause", which is associated with a shock wave resulting from the interaction between ionosphere and the solar wind. This wave is formed when the pressure of the magnetic field induced in the ionosphere (since the magnetic field of Venus is lower than 1/3000 of the terrestrial field) becomes equal to that of the solar wind. The Venusian ionopause plays the same role as the terrestrial magnetopause, i.e., it hinders the solar plasma from penetrating a

*Translator's note. Illegible in the original foreign text.

certain zone around the planet. However, due to the practical absence of the Venusian magnetic field, its distance to Venus is about 100 times smaller than the distance between the magnetopause and the Earth.

What is the explanation for the absence of water?

According to hypotheses which are in acceptance at the present time, the planets were formed almost simultaneously from a giant nebula protoplanetary. Under these conditions, it seems natural to look for common features in all tellurian planets which were concentrated in the same region of the primitive nebula. Contrarily, the results obtained in the last decade showed that the Earth, Mars, Venus, and Mercury were all very different from each other. These differences are certainly due in part to the fact that these stars are not at the same stage of their evolution. The pattern of the latter depends on geometric and mechanical characteristics of the planet, on its distance from the Sun, changes in its interior, etc. Each step is accompanied by the formation or the modification of an atmosphere which thus appears as an important characteristic of the stage of evolution.

As they were formed in the vicinity of the Sun in a region of condensation of iron and silicates, the tellurian planets have essentially retained the heavy components, such as metals, metal oxides, and sulfides. Their atmospheres were formed of gases liberated from volcanic eruptions which accompanied the process of magmatic differentiation, as well as from radioactive disintegration of elements in the interior of the planet. In these emanations, water and carbon dioxide were found in the highest concentrations. Their presence in the atmosphere of Venus is thus readily explainable ...* hydrochloric acid and hydrofluoric acid detected by spectroscopy, or sulfur oxides which should be there if the clouds indeed contain sulfuric acid. A few billion years ago, an atmosphere of similar composition must have

*Translator's note. Illegible in original foreign text.

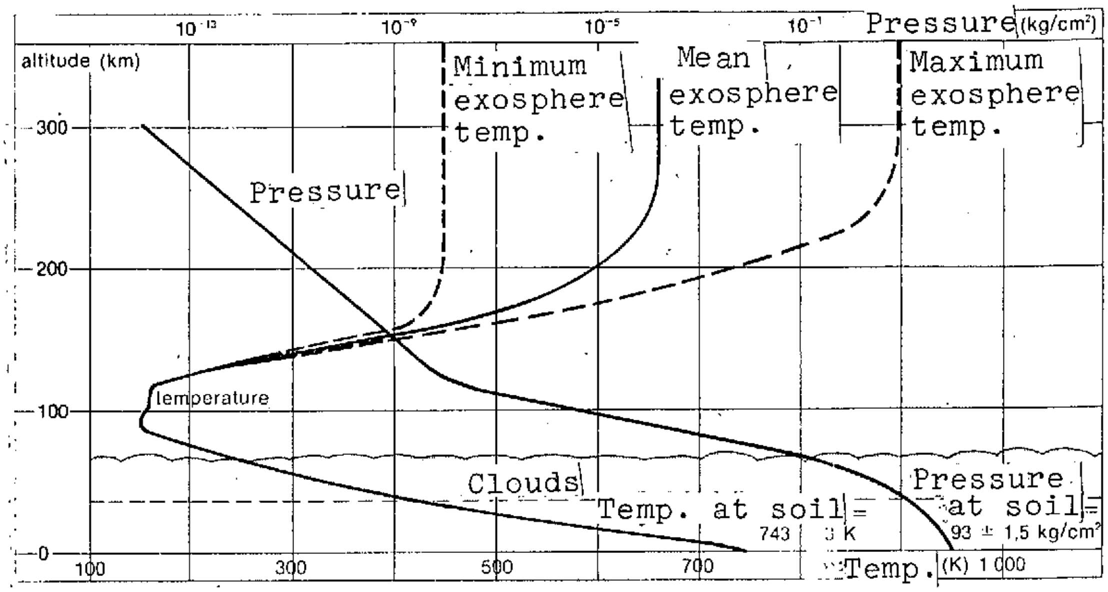

Figure 10. Structure of the Venusian atmosphere up to about 300 km above the soil. The altitude is counted from the center of the planet. The mean temperature of the exosphere varies between 600 and 700 K; during the 11-year cycle which follows the solar activity, it should vary considerably, without any doubt, between the limits indicated in the figure

surrounded the Earth. However, on the latter, the following process subsequently changed the gas blanket completely: the release of free oxygen into the atmosphere, as a result of photosynthesis which accompanied the development of the terrestrial biosphere. This phenomenon led to oxidation of ammonium salts which were also present in the volcanic gases, and thus to the introduction of a large amount of nitrogen into the atmosphere. Carbon dioxide, chlorhydric and fluorhydric acids reacted, on the other hand, with the lithosphere, the hydrosphere, and the rocks, considerably reducing their concentration in the gas phase. Finally, the water, due to the moderate temperature prevailing at the terrestrial surface, could be maintained in the liquid state, and it accumulated essentially in the oceans.

The proximity of Venus to the Sun was certainly the cause of its appreciably different evolution, as suggested by Vinogradov [19, 20]. The decisive factor in this evolution, which is at the origin of the conditions now prevailing on the planet, is undoubtedly the disappearance of the Venusian water.

How to explain this disappearance? There is not valid reason for assuming that the volcanic emanations of Venus did not liberate large quantities of water vapor, as was the case on our planet. Under these circumstances, the mechanism should be sought which is responsible for the fact that there is today thousands of times less water on Venus than on the Earth. The following explanation is a possible one: as a result of the deeper penetration of the solar ultraviolet radiation into the atmosphere, the dissociation of the water vapor into oxygen and hydrogen was undoubtedly much more efficient than on the Earth; the relatively high temperature of the mesopause promoted the subsequent release of hydrogen into space, while the oxygen was fixed in the rocks.

This dryness of the atmosphere, the almost complete absence of oxygen, the very high pressure and temperature, all these features of Venus which appear as original today seem to have been closely interrelated throughout the planet's history. A sufficiently high temperature promotes the release ...* of water into the atmosphere; the drying which we just mentioned favors the carbon dioxide blanket which creates a "greenhouse effect", as a result of which the temperature increases even more. On the other hand, this increase in temperature prevents the appearance of a biosphere in the sense understood today, and, thus, the presence of a large amount of free oxygen.

The large difference between the pressure of carbon dioxide on the Earth (0.0003 atmosphere) and on Venus (almost 100) might lead one to think that our planet is much poorer in this compound, which would be surprising. The truth is that the Earth has the same amount of carbon dioxide as has Venus, but this compound is mainly fixed in the upper part of the Earth's crust. Such a fixation does not occur

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*Translator's note. Illegible in the original foreign text.

on Venus due to the high temperature and the absence of water. If the temperature of our planet was comparable to that of Venus, the pressure of the terrestrial atmosphere would clearly exceed the Venusian pressure, because about 300 atmospheres created by the water vapor would add up to the 100 atmospheres corresponding to carbon dioxide.

In recent years, our understanding of the Venusian phenomena - in particular, of the planet's evolution, its thermal conditions, the nature of its clouds and the characteristics of its surface - has improved considerably. However, we are far from having a solution to all the problems raised by this original star, and Venus will undoubtedly continue to bear the name "mysterious planet" for a long time.

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*Translator's note. Illegible in original foreign text.

VENUSIAN PROBES

The great scientific interest presented by space probes and their important role in the study of planets are clearly expressed in the case of Venus. Indeed, the space probes which have investigated this planet have, by their measurements, considerably increased the volume of our knowledge about this previously little known celestial body. /928

As a matter of fact, Venus is the first planet to have received the visit of a spacecraft, the Mariner-2, which flew over it at a distance of 35,000 km on December 14, 1962. After this experiment, the United States proceeded to two more flights over this star — with Mariner-5 on October 19, 1967, and Mariner-10 on February 5, 1974 (the results of these flights have unfortunately not been available during the writing of this article).

Further, the USSR has conducted a systematic study program of Venus by means of probes which operated inside the planet's atmosphere. These probes, which had a mass of about a ton, comprised two parts (Figure 2): an orbital compartment containing all the systems and instruments which were to function during the Earth-Venus transfer and, in addition, a capsule or planetary compartment which was envisaged for studies in the atmosphere and on the soil of the planet (Figure 3). These spacecraft were placed on a collision trajectory with Venus; when the latter was approached, the capsule separated from the orbital compartment, entered the gas blanket of the planet with a speed of the order of 11 km/sec, and was suddenly slowed down by atmospheric friction. This capsule was built to withstand maximal deceleration of around 300 g, and to survive the heating of its thermal shield (a few thousand degrees in the region of the shock wave). A parachute opened at about 55 km altitude, and the vehicle started to perform measurements.

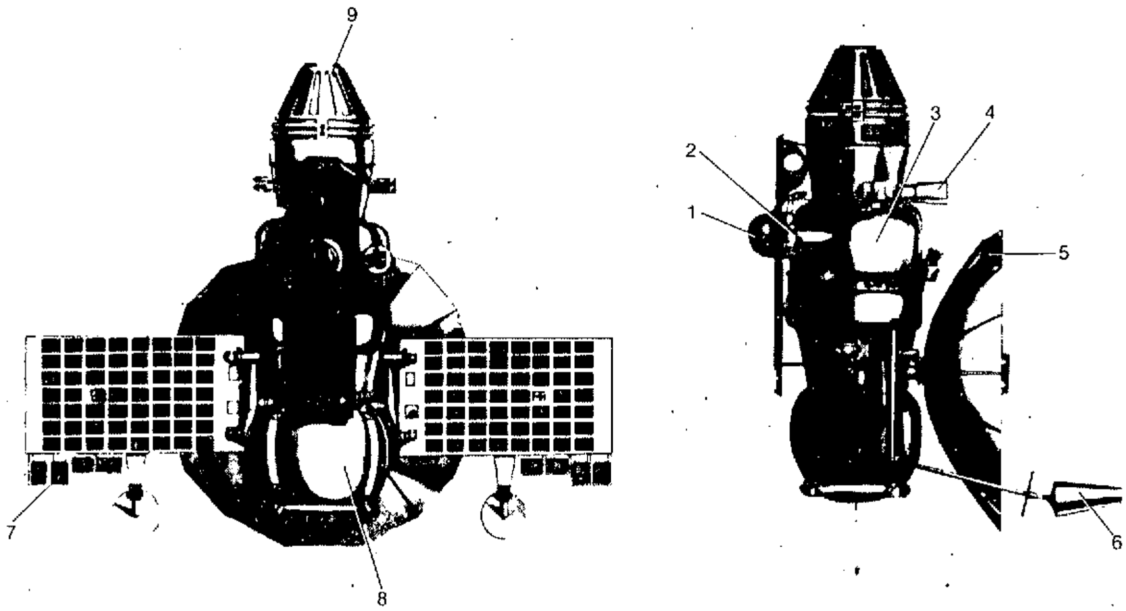


Figure 2. Diagram of the Venus automatic stations:
1, 2, 4 — sensors of the planetary orientation system; 3 — module containing the systems to function during the Earth-Venus transfer; 5 — parabolic antenna; 6 — slightly directional antenna; 7 — solar panels; 8 — compartment intended for descent into the atmosphere

The first success was obtained with Venus-4 on October 18, 1967; the capsule of this probe investigated the atmosphere up to an altitude of 28 km, and was subsequently destroyed by the pressure, which had mounted by then to 20 kg/cm^2. In May, 1969, Venus-5 and Venus-6 penetrated a little deeper into the blanket of Venus. On December 15, 1970, the capsule of Venus-7 was the first to operate on the soil of the planet; however, it transmitted little information from the surface. Finally, on July 22, 1972, the planetary compartment of Venus-8 was the first to send information from the Venusian soil on the illuminated side, for the course of 50 minutes. The structure of the capsule had been improved in the two latter experiments, its thermal protection had been reinforced in particular by adding heat storage batteries. Due to these modifications, the planetary compartment could withstand a pressure of 120 to 150 atm, and could function at an environmental temperature of 800 K.

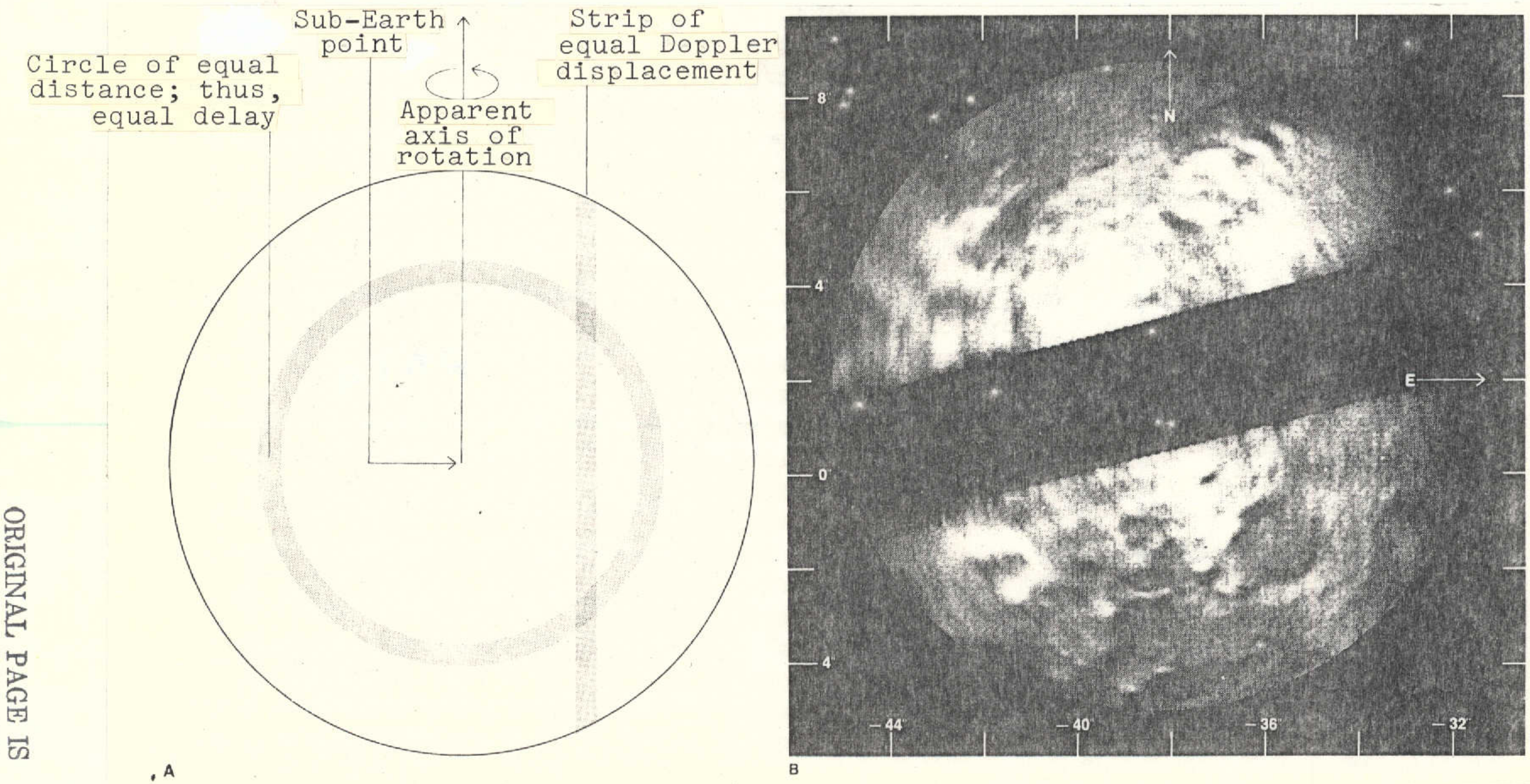
The basic results on the nature of Venus have been obtained due to these important technological achievements. Numerous investigators and specialists took part in this work and contributed to the achievement of the results which form the content of this article. To them the author expresses his gratitude and the gratitude of his colleagues. /931

VENUS PROGRESSIVELY "UNVEILED" BY RADAR

Permanently screened by a thick layer of clouds which surrounds the planet, the Venusian surface is just in the beginning of being discovered by radar soundings. The latter operate on a simple principle (see diagram A) - a radio-electric pulse is sent in the direction of the star and that part of the wave which is reflected by the planet surface is recorded; the echoes which arrive at the receiver with the same delay are reflected by the point of a "circle of equal distance"; those which have the same Doppler frequency shift originate in the points of a strip which is parallel to the planet's apparent axis of rotation. It is thus possible, by analyzing the signal received at a given moment and with a given frequency, to locate the echo corresponding to different points of the investigated hemisphere.

Indeed, one can note a north-south ambiguity in the figure, since the intersection of an equidistant circle and a strip of equal frequency comprises two points.

Two antennas for the reception of the signal must be used in order to remove this ambiguity.


Sub-Earth point
Strip of equal Doppler displacement
Circle of equal distance; thus, equal delay
Apparent axis of rotation
N
E
8
4
0
4
-44
-40
-36
-32
A
B

Until the present time, the resolution of maps obtained by this method was about a hundred kilometers, in the best case (as is the case in Figure 1). But considerable progress was achieved in subsequent years, the importance of which can be felt by examining photo B. This is the most detailed image available to date of the Venusian surface. It covers an area of about 1000 km in diameter in the equatorial region of Venus, and was obtained by Richard Goldstein and colleagues by means of radar probings performed on June 20, 1972, at the radio-observatory of JPL in Goldstone (California): the resolution here is 10 km. The great disclosure of this image is the presence of craters, the largest of which has a diameter of about 160 km and a depth of only 500 m.

Are these volcanic craters? Or are they ancient impact craters formed at a time when the planet's atmosphere was less dense than it is today? The answer to these very important questions is not known at the present time.

While still practically unknown to date, the topographic relief of Venus should be gradually discovered in the next ten years. Investigation of the relief will undoubtedly lead scientists to determine the processes which took place in the past and may still take place today in the interior and on the surface of the planet, and to reconstruct the geological history of the planet. These data will supplement those which are available on the Earth, Moon, Mars, and Mercury, in order to assist the astronomers in understanding the formation and evolution of the solar system.

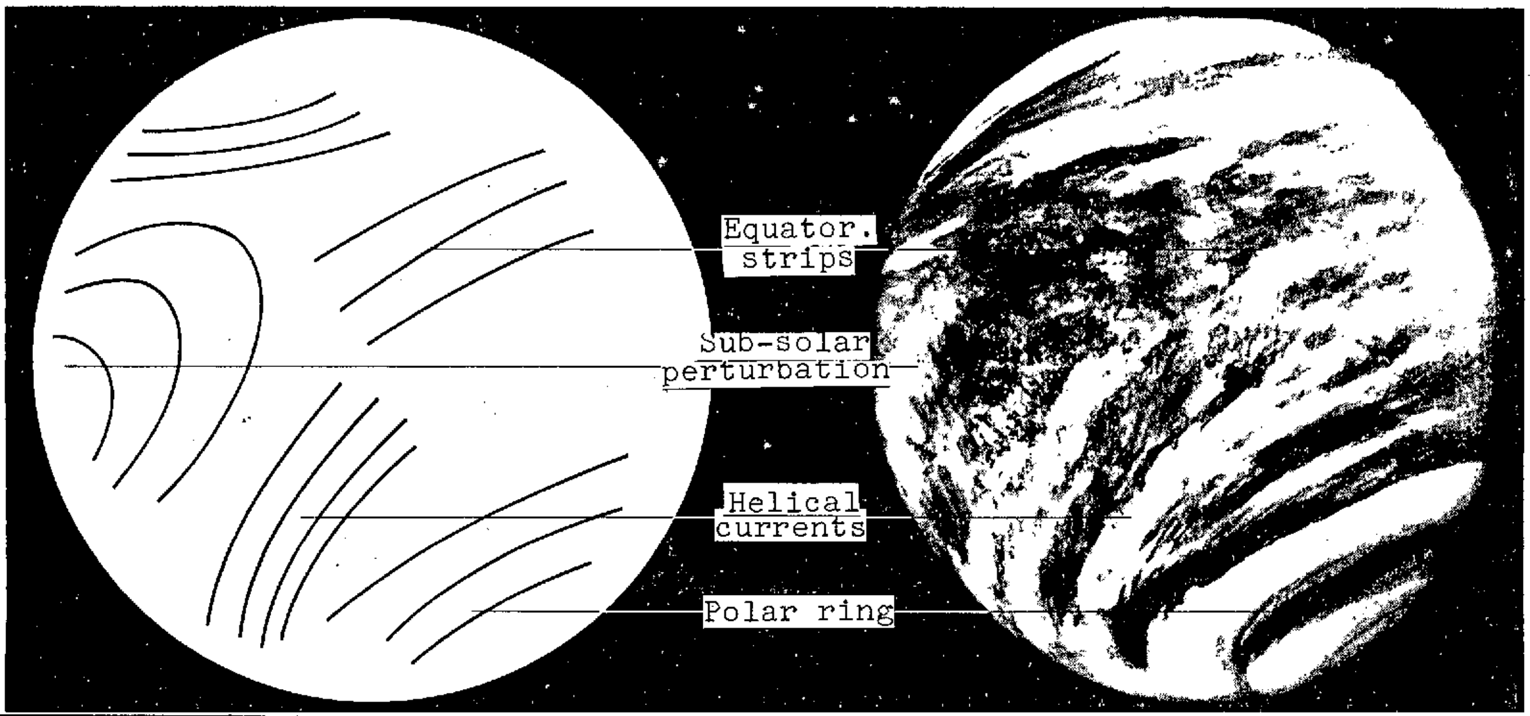
THE CLOUDS OF VENUS SEEN BY MARINER-10

On its way to Mercury, the American probe Mariner-10 flew over Venus at a distance of 5800 km, last February 5. On this occasion it sent about 3400 close-up photographs of the evening star in the course of about 8 days. /937

A part of these photographs, taken in the near ultraviolet range, show dark spots in the region of the high troposphere and low stratosphere. The size of these spots varies from about 10 km to 1000 km. The smallest spots have a life span of only several hours, while the largest spots undergo little change during a period of several days.

According to Bruce Murray et al. [18], by their aspect and movements, the ultraviolet spots attest to the displacement of air masses in the high Venusian atmosphere. Their study has confirmed at first the existence of a zonal rotation of the upper atmosphere in the retrograde direction. This rotation takes approximately 4 days at the level of the equatorial strip, which extends at about 30" latitude, as has been determined from the Earth and according to measurements performed during the descent of Venus probes into the atmosphere (see figure). The zonal movement has a period of about two days at approximately 50° latitude.

But the photographs taken by Mariner-10 revealed the existence of two types of atmospheric formation which had been unknown until the present time. First of all, large perturbation is permanently maintained around the sub-solar point, at 30" latitude, and above 80" longitude. Characteristic spots of convection cells can be seen inside this perturbation.


Equator. strips
Sub-solar perturbation
Helical currents
Polar ring

In addition, a shift of air masses to the poles is superposed on the zonal movement at medium latitudes. Thus, currents are seen which make slow spiral-like movements around the planet, and — after having crossed 200 to 300" in longitude — unite with a ring of polar zonal circulation around 50" latitude. This structure of atmospheric movements at the level of medium latitudes may result from the interaction between a constant sub-solar perturbation and the zonal circulation of the atmosphere. Contrarily to what was thought before, the photograph of the cloud layer surrounding Venus is of great scientific interest, and brings extremely interesting data on the global atmospheric movements and, consequently, on the energy interchanges between different regions of the atmosphere and of the star.